SiGe-Based Power HBTs for High-Frequency Microwave Power Amplification

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ABSTRACT

The design and fabrication of SiGe-based power HBTs, for high-frequency microwave power amplification, are presented. The critical device design parameters have been analyzed in order to achieve high power handling capability and concurrent high power-gain at high operating frequencies. State-of-the-art power performance results obtained from SiGe-based HBTs are described and the difference in frequency responses between common-emitter and common-base HBTs is qualitatively explained. The in-depth analysis presented in this paper indicates the direction to realizing high-performance microwave power HBTs that could be operated in higher microwave frequency range or near-millimeter wave range.

INTRODUCTION

The rapid progress [1, 2], manifested in the reported ever-increasing f_T and f_{max} values, in SiGe-based HBT technology has made this type of devices suitable for high-speed and high frequency microwave applications. One of the major advantages of SiGe HBT is its compatibility with Si CMOS, based on which high-level integration for complex circuit functions is feasible. In wireless communications, high-efficiency transmitters require high-performance active power devices. For this reason, current wireless transmitters operating in microwave frequency ranges are dominated by III-V devices. However, these high-speed devices have some intrinsic disadvantages that make them less accessible for high-level integration, such as poor mechanical strength and low thermal conductivity of the substrate, and relatively high wafer cost. In comparison to the rapid progress on the development of low-power and high-speed SiGe HBTs, the commercial development of *high-power* and high-speed SiGe HBTs is taken at a much slower pace. The major obstacles, which impeded the development of high-power and high-speed SiGe HBTs, are severe heat generation in large-area (needed for high power) devices and power gain reduction under large-signal operations [3]. As a result, for SiGe-based HBTs to be also a contender for wireless high power transmission in high microwave frequency range, the device design and fabrication have to be tailored to minimize the associated thermal effects and maximize device power gain.

In this paper, critical device design parameters are analyzed first, for realizing high-power and high-speed SiGe power HBTs that can be operated at high microwave frequencies. The key fabrication steps to achieve high-performance SiGe HBTs are then described. The characteristics of the state-of-the-art SiGe power HBTs are presented followed by a qualitative analysis of difference in frequency response between common-emitter and common-base configurations.

DEVICE DESIGN AND TECHNOLOGY

Mesa-type structures are widely used in advanced microwave power HBTs. In this work, a double-mesa structure was employed to make Si/SiGe/Si power HBTs [4]. Figure 1 shows the schematic of a finished double-mesa type SiGe HBT. This mesa structure HBT fabricated after one-step growth may limit the minimum feature size of the emitter finger with conventional wet/dry etching technology. However, the analysis presented in the following shows that the emitter feature size is less critical for high power HBTs than for low-power and high-speed HBTs. All analyses with regard to device critical parameters and fabrication technology that follow are based on this double-mesa structure.

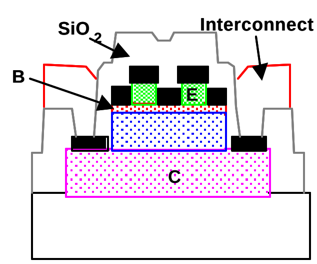


Figure 1. Schematic of double-mesa type SiGe HBT.

Figure of Merit for power HBT frequency response: The device-designing goal for high power and high-speed SiGe HBTs is to allow devices to be able to deliver high output power while exhibiting fast response at high microwave frequencies. These two requirements set contradictory limitations to each other under certain situations. For devices used for power amplification, the device frequency response is characterized by the maximum frequency of oscillation, f_{max}, which can be expressed as

$$f_{\max} = \left(\frac{f_T}{8\pi R_B C_{BC}}\right)^{\frac{1}{2}} \tag{1}$$

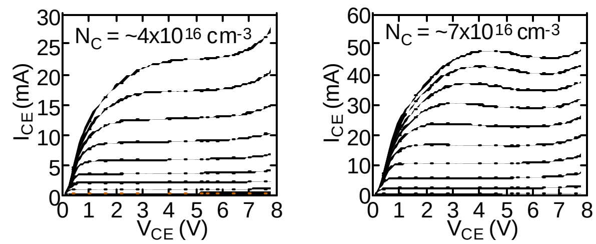
where f_T is cut-off frequency an R_B and C_{BC} are base resistance and base-collector junction capacitance, respectively. Therefore, in order to improve device frequency response the device vertical structure and layout need to be optimized for a high f_{max} value.

Ge composition and profile: It is necessary to have a well-defined Si/SiGe heterojunction that coincides with emitter-base PN junction in order to enhance the power gain of large-area SiGe-based HBTs. Such a heterojunction provides significantly enhanced emitter injection efficiency, which can be traded with a highly doped base region while maintaining a reasonable current gain. Since the maximum Ge composition ought to be at the emitter-base junction and a down slope-graded Ge profile from base-emitter junction to base-collector junction retards the carrier transportation across the base region, a uniform Ge profile ("box-type") thus becomes the appropriate choice. The maximum Ge composition that can be employed is mainly determined by the considerations of alloy-scattering limited carrier mobility. Previous study [5] has shown that ~35 atom% but <40 atom% Ge might be the maximum composition percentage for maximizing the minority carrier mobility in the base region.

Base doping concentration: It has been found that, for power HBT applications, a high doping level in the base region is always preferred. Practically, the maximum doping concentration is usually set by the doping capability of growth facilities. A high doping concentration in the base region offers the following advantages: 1) reduction of base sheet resistance. A lower base sheet resistance can tolerate larger emitter finger width, which is determined by emitter current crowding effect. High power density is therefore can be achieved in unit emitter length; 2) base metal contact resistivity can be reduced to a negligible level, such that the width of the base contact metal can be made small [6]. A narrower base contact metal further results in smaller base-collector junction capacitance (the extrinsic portion); and 3) a thinner base region can be employed which can further reduce the base transit time without emitter-collector punch-through concern. Although the minority carrier mobility is reduced with increasing base doping concentration, the enhancement of base transit time (τ_B) exceeds the concurrent opposite effects due to mobility degradation, as it can be see in the following expression

$$\tau_B = \frac{q W_B^2}{2kT\mu_{n,B}} \tag{2}$$

where W_B is base region width and $\mu_{n,B}$ is minority carrier mobility in the base region.



(a) (b)

Figure 2. I-V curves measured from HBTs fabricated from Si/SiGe/Si heterostructures with different doping concentrations in the collector layer: (a) ~4x10^{16}cm^{-3} and (b) ~7x10^{16}cm^{-3}.

Collector thickness and doping concentration: The collector design influences both device thermal effects and device speed, in addition to the base-collector breakdown characteristics. Low-power, high-speed SiGe-based HBTs require high cut-off frequency, f_T, in addition to f_{max}, which has been achieved via shrinking the device vertical dimensions [1, 2]. The doping concentration in the collector (epilayer) of the most advanced SiGe HBTs was also increased to a high level for the purpose of high speed and proper breakdown voltages. It has been little noticed, previously, that a high collector doping concentration for large-area devices can result in severe thermal effects during device operation. Thermal effects are less observable in low-power (very small emitter area) devices than in high-power (large emitter area) ones, mainly because the power level in small devices is low and thus heat generated within the devices can be easily dissipated. Figure 2(a) and 2(b) shows the I-V curves of two SiGe HBTs (emitter area 312 μm^2), which were fabricated from two similar heterostructures with the only difference of collector doping concentrations. The I-V curves were measured with identical base current step size. The device (Fig. 2(a)) fabricated from the heterostructure that has a collector of low doping concentration exhibits lower collector current density than the other (Fig. 2(b)), of which the collector is doped more heavily. It is also noticed that the maximum collector current (limited by Kirk effect) is largely proportional to the collector doping concentration. Of more importance, the thermal effects, exhibited in the device fabricated from heterostructure with more lightly doped collector, are negligible in comparison to the other. The thermal effects difference is due to the fact that larger current density generates more heat and thus causes more temperature rise in the device than smaller current density under the same capacity of heat dissipation It thus can be concluded that good thermal conductivity of Si is still not an assurance for fabricating thermal effects-free SiGe-based HBTs, provided that the collector doping concentration is not made enough low. A thicker collector is usually employed for devices when the collector doping is made lower, such that the collector layer is fully depleted during operation. The power device frequency response (f_{max}) versus collector thickness (W_C) has been derived in Ref. 3 and its experimental proof can be found in Ref. 7. Overall, employing a thick and lightly doped collector favors a high maximum oscillation frequency (f_{max}) and also helps reduce the detrimental thermal effects in the device. It is noteworthy that a thick collector increases the carrier transit time in the collector space charge layer ($\boldsymbol{t}_{CSCL}$) and therefore decreases the cut-off frequency (f_T). Nevertheless, the benefits (reduction of C_{BC} and thermal effects, higher breakdown voltage and linearity) obtained from using a thicker collector exceed its adverse effects arising from the reduction of f_T. Additionally, $\boldsymbol{t}_{CSCL}$ can be enhanced with a launch layer [7] placed on the collector side near the base-collector junction. In comparison to the parameters discussed above, other heterostructure parameters related to emitter, subcollector (buried layer) and substrate *etc*. are also important but less critical than the ones discussed above in power HBT design.

Large-area device layout: The critical layout parameters that influence the device speed, power handling capability and thermal effects are: total emitter area, number of emitter fingers, finger width, length and arrangement (grouping) and base contact metal width. A detailed description with regard to the selection of these parameters can be found in Ref. 3.

Fabrication: The fabrication process of double-mesa type SiGe-based HBTs has been detailed by Rieh *et al.* [4]. In order to reduce the major frequency limiting capacitance (C_{BC}) and other parasitic capacitance, an isotropic etching process has been developed in this study to remove the collector material under the base contact metal. A similar isotropic etching process was also used to make air bridges between device active area and interconnect contact pads. The SEM picture of a finished device using such process is shown in Figure 3. An overhung base contact metal and air bridges have been successfully fabricated.

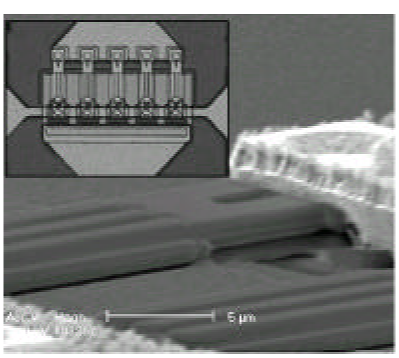


Figure 3. SEM picture of a 15-emitter finger SiGe HBT. The air bridges are formed using isotropic dry etching.

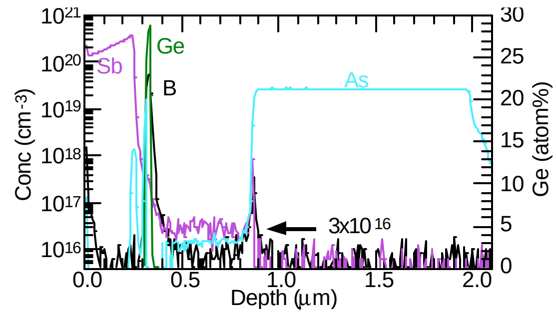


Figure 4. SIMS profile of the MBE-grown Si/SiGe/Si heterostructure.

RESULTS

Both CVD and MBE were used to grow Si/SiGe/Si heterostructure in this study. Figure 4 shows a typical SIMS profile grown by MBE. High doping level (~10^{20} cm^{-2}) was achieved in the base region and low doping concentration ($3x10^{16}$ cm^{-2}) was employed in the collector layer. The Ge composition in the base region is 30 atom%. Small-signal S-parameters were measured on a SiGe HBT with 9-emitter finger and 403 μm^2 total emitter area under both common-emitter and common-base operations. Figure 5 shows the calculated power gain versus frequency of this device. An f_{max} of 100 GHz can be estimated from –6dB/oct extrapolation when the device is operated in the common-base mode. This is the highest f_{max} value that was reported for large-area (>400 μm^2) SiGe-based HBTs up to date. An f_T of 35 GHz was also measured from the same device when it was operated in the common-emitter mode, which results in a value of $f_T \bullet BV_{CEO}$ larger than 400 GHz•V. Again, this is the highest reported $f_T \bullet BV_{CEO}$ value.

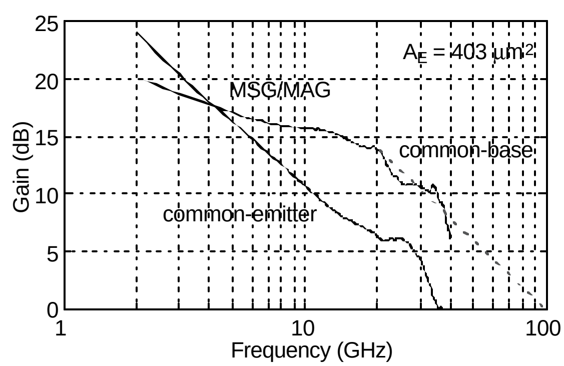


Figure 5. Small-signal RF response of a 9-emitter finger SiGe HBT.

Figure 6 shows the output power, P_{out}, power gain, and power added efficiency, *PAE*, versus input power, P_{in}, for a 20-emitter finger HBT (fabricated from CVD grown wafer) operating at f = 8.4 GHz, under common-emitter and common-base operations, respectively. An output power of 27.4 dBm was obtained at the peak *PAE* of 33% with concurrent power gain of 7 dB in the common-base mode. This output power represents the highest power level ever reported from a single SiGe-based HBT that was operated at X-band. Power performance characteristics were also measured at f = 12.6 GHz on a 15-emitter finger SiGe HBT fabricated from a MBE-grown heterostructure. Figure 7 shows the measured P_{out}, power gain, and *PAE* versus P_{in}. An output power of 22.3 dBm was measured at peak *PAE* of 22% with concurrent power gain of 7 dB. These results declare the first SiGe-based power HBT that was operated at Ku-band.

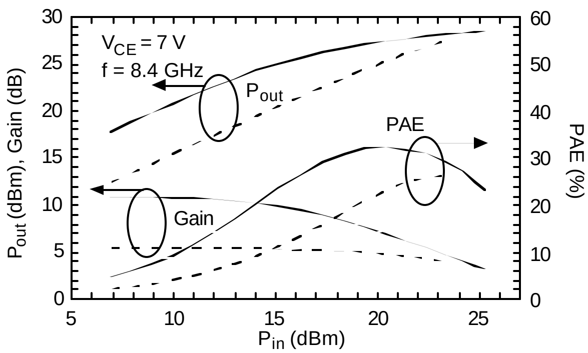


Figure 6. Measured output power, power gain and power added efficiency vs. input power for 20-emitter finger SiGe HBTs (A_E = 1560 μm^2) at 8.4 GHz. Solid lines: common-base mode, dashed lines: common-emitter mode.

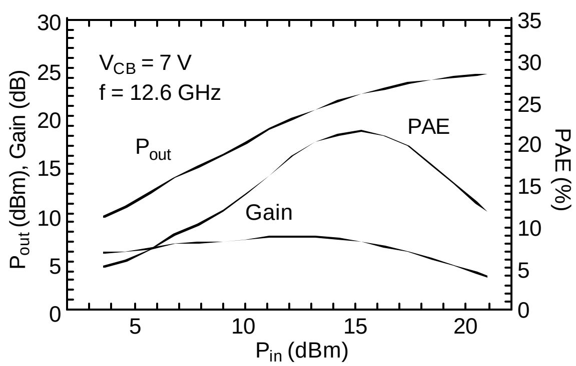


Figure 7. Power performance of 15-emitter finger SiGe HBTs (A_E = 670 μm^2) operated at 12.6 GHz.

It is apparent (Figs. 5 and 6) that a higher power gain and thus better large-signal performance are constantly available when the device was operated in the common-base mode than in the common-emitter mode. It has been realized that, in the common-base configuration, the major limiting capacitance between port 1 (base) and port 2 (collector) is C_{BC}, while in the common-emitter configuration it is C_{EC} that sets the frequency response characteristics. Since C_{EC} is largely (considering parasitic capacitance) the capacitance of serially connected two junctions (C_{BE} and C_{BC}), which is always smaller than C_{BC}, faster frequency response (higher power gain under the same frequency of interest) is expected when the device is operated in the common-base mode than that in the common-emitter mode. This difference in frequency response is further examined by comparing S_{21} versus frequency in the two configurations (Fig. 8). Because C_{BC} is large than C_{EC}, the -6dB/oct turning point (first pole) occurs earlier in the common-emitter configuration than in the common-base configuration. Since no f_T, but f_{max}, can be measured from the common-base configuration, f_T should not be considered as a figure of merit for evaluating the device speed when the device is used for power amplification.

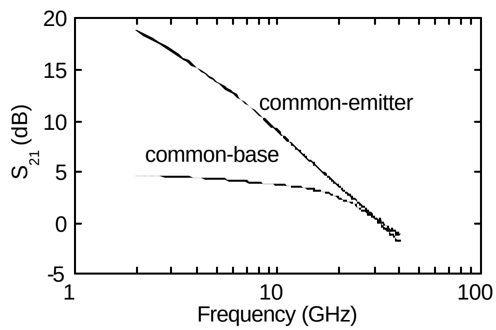


Figure 8. Comparison of S_{21} vs. frequency between common-emitter and common-base modes.

CONCLUSION

An in-depth analysis of critical design parameters was presented with the description of the state-of-the-art power performance characteristics of SiGe-based power HBTs. In order to achieve high-power handling capability (with minimal thermal effects) and simultaneous high-speed large-signal operation, the critical design parameters for both vertical and layout structures have to be well selected and the fabrication process has also to be optimized. Further improvement of SiGe-based HBTs along this predefined direction could lead this type of devices into successful operations in higher frequency microwave and near-millimeter wave range.

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